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Radio-Controlled-Submarine Model for Engineering Education

Khaleed Al-Hindi, Majed Al-Muallem, Ghali Al-Adwani, Khaleed Faqiha, Ragheed Bantan, and Akrm Zamzami
College of Engineering and Islamic Archetacture, Umm Al-Qura University, Mekkah, Saudi Arabia

Supervisor: Prof. Dr. Ahmed Farouk AbdelGawad
Vice Dean for Graduate Studies and Research, Faculty of Engineering, Zagazig University, Egypt, afaroukgb@gmail.com

Abstract– The objective of this work is to inspire students' interest in interdisciplinary engineering through the design, fabrication and operation of a radio-controlled-submarine model in B.Sc. graduation project. The model was remotely controlled by a radio-signal unit. Students proposed simple, but effective, approaches for the operation mechanisms and control needs of the submarine model. Generally, students succeeded in constructing and testing their model for surface operation. However, they faced some difficulty in the implementation of the model for underwater operation. In any case, their work represents a good practical experience for such type of models.

Keywords—Radio control, Submarine models, Hands-on learning, Engineering education.

I. INTRODUCTION

A. Importance

For centuries people dreamed of navigating under the sea, but it was not until the beginning of the twentieth century that inventors succeeded in developing practical submarines. With the coming of World War I, nations saw something entirely new in war: the deadly effectiveness of underwater craft, with German U-boats threatening to starve Britain and bringing the United States into the war, thus proving underwater battles more important than the great battles fought on land. A generation later U-boats repeated the struggle in the Atlantic, while in the Pacific U.S. submarines literally put Japan out of business. Then in the nuclear age, the true submarine became the most powerful weapon of war ever created, the weapon that paradoxically kept the peace [4]. More about submarine history can be found in [1]-[6]. The submarine development and technology is a very interesting topic that was covered by many researchers [7]-[11]. Recently, the unmanned marine vehicles, especially submarines attracted various research work [12]-[16]. Other publications concerning innovation [17]-[19] and hand-on learning techniques [20]-[22] may also be found. The present work is a practical exercise of engineering students to design, fabrication, and operation of a radio-controlled model of the Seawolf submarines that will be illustrated in the next section. It was chosen by the students for its famous reputation and attractive hydrodynamic shape.

B. Seawolf Submarines

Seawolf submarines represent a class of nuclear-powered fast attack submarines (*SSN*) in service with the United States Navy, Fig. 1. The design work of this class began in 1983 [23]. Originally, an intended fleet of 29 submarines was to be built over a ten-year period, then reduced to only twelve submarines. However, the end of the "cold war" and subsequent budget constraints led to the cancellation in 1995 of any further additions to the fleet, leaving the Seawolf class limited to just three boats [24]. These three submarines are named as: *USS* Seawolf (*SSN21*), *USS* Connecticut (*SSN22*), and *USS* Jimmy Carter (*SSN23*) [25]. The Seawolf class cost about $3 billion ($3.5 billion for *USS* Jimmy Carter). Thus, it is the most expensive *SSN* submarine and second most expensive submarine ever after the French *SSBN* Triomphant class [24]. Table 1 shows the overall specifications of the Seawolf submarine.

Fig. 1. Seawolf nuclear-powered attack submarine "*USS* Jimmy Carter" (*SSN 23*) [25].

Table 1. Overall specifications of the Seawolf submarine [25].

Item	Description
Builders	: General Dynamics Electric Boat Division
Power Plant	: One nuclear reactor, one shaft
Displacement	: 9,137 tons submerged (12,139 tons for *USS* Jimmy Carter)
Length	: 353 *feet* [107.59 *m*] (453 *feet* [138.07 *m*]for *USS* Jimmy Carter)
Hull Diameter	: 40 *feet* [12.19 *m*]
Draft	: 35 *feet* [10.67 *m*]
Speed	: 25+ *knots* (28+ *miles/h*, 46.3+ *km/h*)
Diving Depth	: 800+ *feet* [244+ *m*]

II. Present RCSS Model and Objectives

The present radio-controlled submarine (*RCSS*) model resembles, as much as possible, the classic type of Seawolf submarines (*SSN21* and *SSN22*). Due to some fabrication and technical difficulty, there are few differences between the real-life Seawolf submarine and the present model. However, general features of the Seawolf submarine are maintained.

The objective of this work is to inspire students' interest in interdisciplinary engineering through the design, fabrication and operation of a radio-controlled-submarine model in B.Sc. graduation project. The model was remotely controlled by a radio-signal unit. Students had to gain skills in mechanical design, material selection, fabrication, control, radio-signal transmission, software application, etc.

III. Design of the Present RCSS Model

The model length is 1.60 *m*, which represents a scale of 1:67 with the full-scale submarine (*SSN21*). Following the same scale, the diameter of the model had to be 0.18 *m*. However, the diameter of the model was increased by 33.33% to be 0.24 *m* to facilitate the fixation of different components inside the model body as will be seen in coming sections.

A. Design and Drawings

The design and drawings of the different parts of *RCSS* model were carried out by "Autodesk Inventor 2011" [26]. The main dimensions of the model were taken from Table 1 with the scale of 1:67. After considering different available materials, it was decided to use fiberglass for the outer body and rudders of the submarine model. This choice was based on some advantages, namely: (*i*) ease of fabrication, (*ii*) low cost, (*iii*) low weight, and (*iv*) reliability and sustainability. The dimensioned detail-drawings were used to fabricate the different parts of the submarine model.

B. Stress Analysis

To ensure that the hull of the *RCSS* model will resist the hydrostatic pressure of the water head in case of diving, stress analysis was carried out using "Autodesk Inventor 2011" [26]. The analysis was carried out for a maximum water depth of 3 *m*. This gives a corresponding hydrostatic pressure of 0.02943 *MPa*. Table 2 illustrates the values of the general characteristics and properties that were used in the analysis. The material of the model hull is fiberglass. Results covered mainly Von Mises, first principal, and second principal stresses. As expected, the results revealed that the design of *RCSS* model with fiberglass as the hull material was very safe. Figure 2 shows a sample of the results.

Table 2. Values of the characteristics and properties for the stress analysis.

No.	Item	Value
1	Water density	1000 kg/m^3
2	Mass of *RCSS* model	38.6346 *kg*
3	Projected area of *RCSS* model	0.975229 m^2
4	Volume of *RCSS* model	0.0386346 m^3
5	Simulation type	Static analysis (Stationary *RCSS* model)
6	Mesh average element size (fraction of model diameter)	0.1
7	Mesh minimum element size (fraction of element average size)	0.2

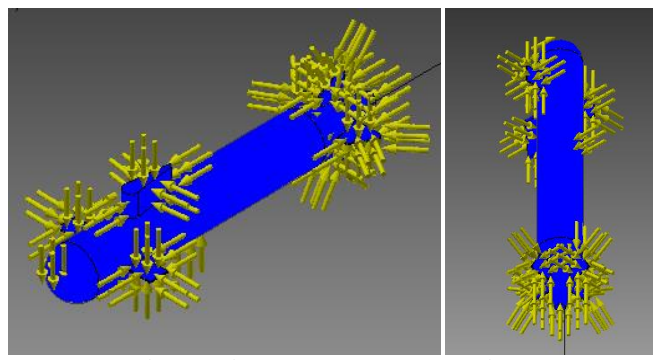


Fig. 2. Sample of results of stress analysis (Two views of Von Mises Stress).

IV. Control of Present Submarine Model

A. Control Components

The control system of the present model was divided into subsystems. Each subsystem was designed and implemented to carry out certain job.

A.1. Water Gear Pump

A water gear pump [27], Fig. 3, was used to fill and empty the water tank. This water tank was used to lower or raise the submarine in the water. Table 3 shows the specifications of the pump.

Fig. 3. Miniature *DC* water gear pump [27].

Table 3. Specifications of the water gear pump [27].

Item	Description
Model	: RS-360SH Miniature *DC* Water Pump
Water Flow	: about 1.2 *l/min* (@ 5V)
Motor Diameter	: 27 *mm*
Pump Width	: 45 *mm*
Outlet Diameter	: 4 *mm*
Pump Length	: 60 *mm* (excluding terminals)
Weight	: 70 *g*
Type	: Water
Operating Voltage	: 3~9 *V*
Running mode	: Two running modes (Forward and Backward)

A.2. MINI Electronic Speed Control (ESC) (Forward & Reverse)

An electronic speed control (*ESC*) [28], Fig. 4, was used to vary the speed and direction of the electric motor of the water pump. It was used in conjunction with the receiver of the radio-control system. Table 4 shows the specifications of *ESC*.

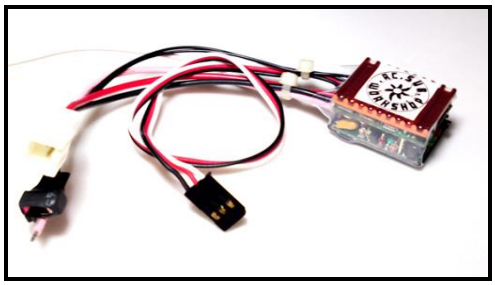


Fig. 4. Electronic speed control (*ESC*) [28].

Table 4. Specifications of MINI *ESC* [28].

Item	Description
Features	: High frequency motor speed, one touch set up led, forward & reverse, led indicator.
Operating voltage	: DC 4-12*V*
Maximum pulse current	: 50 *A*
Maximum continuous	: 10 *A*
Frequency (output)	: 1 *KC*
Internal resistance (ohms)	: 0.008×2
Dimensions	: 20×28×15 (*mm*)
Weight	: 50 *g*

A.3. Waterproof Brushless Motor

A waterproof brushless motor [29], Fig. 5, equipped with 50*A* electronic speed control (*ESC*), was used to drive the submarine model. Table 5 shows the specifications of waterproof brushless motor. A suitable propeller was fixed to the motor shaft.

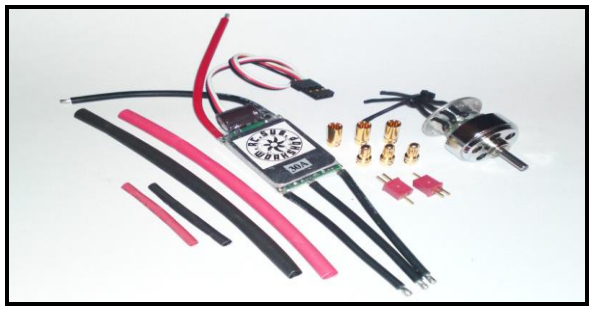


Fig. 5. Waterproof brushless motor, equipped with 50*A* electronic speed control [29].

Table 5. Specifications of waterproof brushless motor [29].

Item	Description
Features	: Support the reversing function, automatic learning throttle, close the error signal power, single 3.0V LIPO protective voltage, supports most models sensor-less brushless motor
Voltage range	: 4.8-15*V*
Resistance	: 0.003 *MR* (30*A*)
Continuous working current	: 30*A*
Instant current	: 50*A* (10 seconds)
PWM frequency	: 8K/16K/32K
Motor speed	: up to 30000 *RPM*
Weight	: 50*g*

A.4. Electronic Speed Control

VXL-3M electronic speed control [30], Fig. 6, was used to change the speed of the motor that drives the submarine model. Table 6 shows the specifications of the electronic speed control.

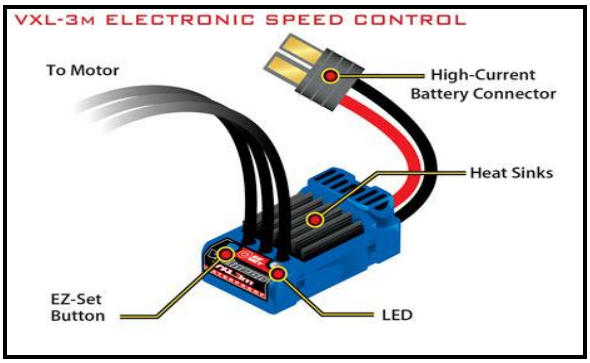


Fig. 6. VXL-3M electronic speed control [30].

Table 6. Specifications of VXL-3M electronic speed control [30].

Item	Description
Input voltage	: 6 to 12 cells NiMH, 2S to 3S LiPo
Case Size	: 26.5 *mm* Width × 46.5 *mm* Depth × 22 *mm* Height
Weight	: 38 *g*
Motors	: Sensorless Brushless
Motor Limit	: None
On Resistance	: 0.0005 *Ohms*
PWM Frequency	: 12,000 *Hz*
Peak Current	: 150 *A*
Continuous Current	: 52 *A*
BEC Voltage	: 6.0 *V - DC*
Motor/Battery Wiring	: 16-Gauge Maxx® Cable
Transistor Type	: MOSFET
Low Voltage Detection	: 2-Stage indicators, switchable (on or off)
Thermal Protection	: 2-Stage thermal shutdown
Profile selection	***Sport Mode:*** 100% fwd, 100% brakes, 100% rev ***Race Mode:*** 100% fwd, 100% brakes, no rev. ***Training Mode:*** 50% fwd, 100% brakes, 50% rev.
Single-button setup	: Yes, Traxxas EZ-Set®
Battery Input Connector	: Traxxas High-Current Connector
Motor Connector	: TRX 3.5 *mm* Bullet Connectors

A.5. LiPo Battery

A battery of type "Duratrax Onyx Sport HC LiPo Stickpack 7.4*V* 4200*mAh* 35C" [31], Fig. 7, was used to power the water pump. Table 7 shows the specifications of the battery.

Fig. 7. LiPo battery [31].

Table 7. Specifications of LiPo battery [31].

Item	Description
Manufacturer	: Duratrax
Voltage	: 7.4*V*/ 2*s*
Battery Configuration	: Stick
Battery Capacity	: 4200*mAh*
Battery Type	: LiPo
Battery Application	: Power Packs
'C' Rating	: 35C

A.6. Led Acid Battery

A led acid battery, Fig. 8, was used to power the motors of the submarine model. The voltage of the battery is 12 *V*-DC with rating current of 6 *A*.

Fig. 8. Led acid battery.

A.7. Radio-Control Unit

A radio control unit was used to remotely control the motion of the submarine model. The control unit was consisted of two main parts as follows [32]:

(i) Transmitter:

This unit was of the type "XG7 EG (w/ NET-K337G RG831B/RA01T DS831(3))", Fig. 9. The unit is to operate using radio signal type of "NET-K337G" with receivers of type "RG831B/RA01T", and servos of type "ES539(3)".

(ii) Receiver:

It was 8-channel receiver of type "RG831B (DMSS 2.4 *GHz* 8-channel Receiver)", Fig. 10. The specifications of the receiver are illustrated in Table 8.

Fig. 9. Radio transmitter [32].

Fig. 10. Radio receiver [32].

Table 8. Specifications of the 8-channel receiver [32].

Item	Description
Features	: Coaxial Antenna, Remote Antenna (RA01T)Attached, Telemetry Module (Incorporated in remote antenna)
Dimensions	: 14.5 *mm* × 25.5 *mm* × 48 *mm*
Weight	: 15 *g*
System	: DMSS 8ch
Rated Voltage	: 4.8 *V*
Operating Voltage	: 4.0-8.5 *V*

A.8. Servo Micro-Motor

A high-torque standard servo [33], Fig. 11, was used to adjust the angle of the rudders of the submarine model. The specifications of the servo at 6 *volts* are shown in Table 9.

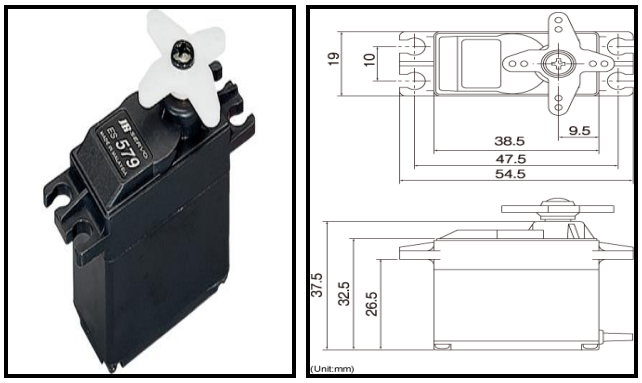


Fig. 11. Servo Micro-Motor [33].

Table 9. Specifications of the servo micro-motor [33].

Item	Description
Type	: ES579
Toque	: 9.50 *kg.cm*
Dimensions	: 19.0 *mm* × 54.5 *mm* × 40.5 *mm*
Weight	: 48.0 *g*
Speed	: 1.9 *sec/cycle*
Ball Raced	: Yes

B. Operation of Radio Control Unit

B.1. Transmitter Operation

Figure 11 shows how the orders (commands) are transmitted by the transmitter of the control unit to remotely control the moving components of the submarine model. The integration of these orders facilitate the correct operation of the submarine model. The available channels of the radio-control unit are fully utilized. Referring to Fig. 12, table 10 summarizes the main switch commands.

Fig. 12. Transmitter main operation control switches.

Table 10. Main switch commands of the transmitter.

No.	Switch	Switch Movement	Function control
1	Main in middle	Up and down	Operation switch "on" and "off"
2	Left-hand	Up and down	Propeller: "Forward" and "Reverse"
3	Left-hand	Left and right	Water pump: "Filling" and "Emptying"
4	Right-hand	Up and down	Diving rudder: "up" and "down"
5	Right-hand	Left and right	Turning rudder: "Left" and "Right"

B.2. Receiver connections

The channels of the receiver, Fig. 10, are connected as shown in Fig. 13.

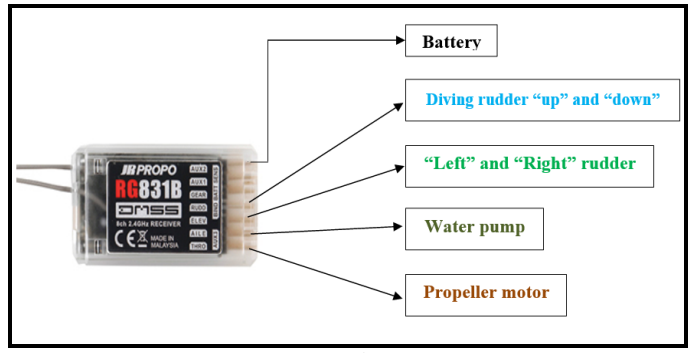


Fig. 13. Connections of receiver channels.

V. Fabrication and Assembly of RCSS Model

A. Details of Fabricated Parts

The present fabrication process followed the guidelines and descriptions that are mentioned in the "Forums of Nautilus Drydocks" [34].

A.1 Outer Body (Hull)

The outer body was fabricated from fiberglass. At the beginning, a foam model was completely fabricated by the students to adjust the shape and dimensions, Fig. 14a. Then, a wooden mold was fabricated using a suitable lathe in a commercial workshop. The outer surface of the mold was carefully finished and smoothed, Fig. 14b. Then, the centerline, which divides *RCSS* model into two similar parts was marked on the outer surface of the mold, Fig. 15.

Fig. 14a. Foam model and wooden mold. Fig. 14b. Finishing and smoothing the surface of the wooden mold.
Fig. 14. Foam model and wooden mold.

Fig. 15. Marking the cenerline of the wooden mold.

The wooden mold was rested in a wooden bed, Fig. 16, such that only the upper half of the mold was above the bed. The marked centerline, Fig. 15, guided the right positioning of the wooden mold. The surface of the wooden mold was covered by a special wax as a parting/release agent. Then, fiberglass was casted as the body material, Fig. 17. Thus, two halves of *RCSS* model were sequentially obtained, Fig. 18.

Fig. 16. Mold in the wooden bed [34].

Fig. 17. Casted fiberglass on the wooden mold [34].

Fig. 18. Casted half of *RCSS* model body.

The two halves were left untill fiberglass fully dried and they were ready for machining and surface finishing. Then, the two halves were assembled together. The surface of *RCSS* model was coated with a suitable primer. The nose and most of the upper half were cut to facilitate fixation and maintenance of various components of the control system and the operating mechanisms, Fig. 19. Most of the lower half of the *RCSS* model was closed and used as a water tank for the model diving and flotation.

Fig. 19. Assembled two halves of the *RCSS* model.

A.2 Main Sail

The fabrication of the main sail is divided into two steps. The first step concerns the fabrication of the base sail. A wooden mold was fabricated according to the required dimensions, Fig. 20. Then, fiberglass sheets were casted around the mold. After the drying of fiberglass the mold was removed and a hollow base sail was obtained.

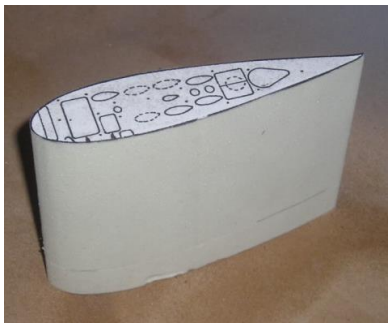


Fig. 20. Wooden mold of the base sail [34].

The second step concerns the fillet on the front of the base sail that serves as streamlining and helps counter the snap roll phenomenon. It was fabricated from wood, Fig. 21, and attached to the base sail by suitable glue, Fig. 22. Then, the main sail was coated by primary coating and painted in black, Fig. 23. The main sail was fixed in its position on the model hull using glue.

Fig. 21. Wooden fillet of the front of the base sail [34].

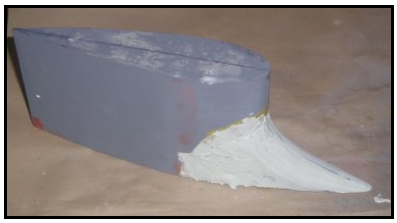


Fig. 22. Wooden fillet is glued to the base sail [34].

Fig. 23. Final assembly of the main sail.

A.3 Rudders

As can be seen in Fig. 19, there are six rudders connected to *RCSS* model. Two similar front horizontal rudders and two similar rear horizontal rudders for diving and flotation. Two similar rear vertical rudders for steering. These rudders were made of fiberglass also. Three wooden molds were fabricated and fiberglass sheets were casted on them to produce the required rudders in a process similar to that of the hull production, Fig. 24a. The rudders were connected to the hull by short metal rods. These rods were fixed in the rudders in the phase of the fiberglass drying, Fig. 24b.

Fig. 24a. Wooden mold [34].

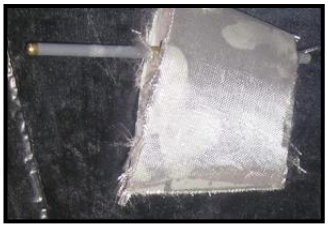


Fig. 24b. Fiberglass rudder [34].

Fig. 24. Rudder fabrication.

A.4 Mechanisms

As can be seen in Fig. 25, there are two simple mechanisms to move the horizontal and vertical rudders. The servo micro-motors drive the mechanism based on the signal from the radio control unit. Each mechanism is consisted of metal rods, levers, screws, bolts, *etc*. The first mechanism moves the four front and rear horizontal rudders, Fig. 26. The second mechanism moves the vertical two rear rudders, Fig. 27.

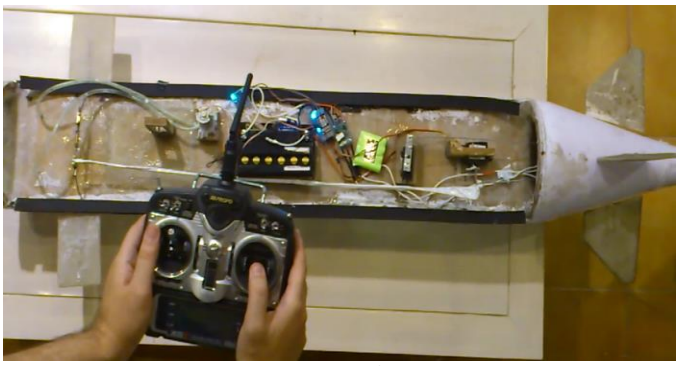


Fig. 25. General view of *RCSS* mechanisms.

Fig. 26a. Servo micro-motor.

Fig. 26b. Front horizontal rudders.

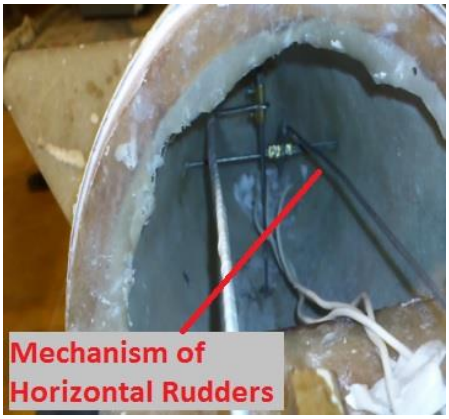


Fig. 26c. Connections to rear horizontal rudders.

Fig. 26d. Movement of rear horizontal rudders.

Fig. 26. Mechanism of the four front and rear horizontal rudders.

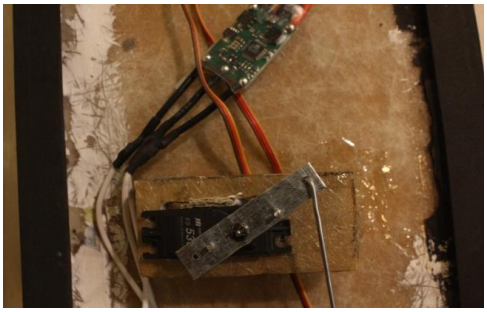


Fig. 27a. Servo micro-motor.

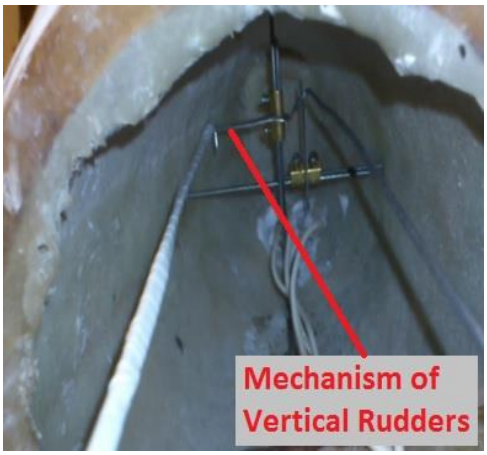


Fig. 27b. Connections to rear vertical rudders.

Fig. 27c. Movement of rear vertical rudders.

Fig. 27. Mechanism of the two rear vertical rudders.

B. RCSS Assembly

Figure 28a shows the inside of *RCSS* model with all components are assembled. Three round metal masses were added for model balance. The outer half of the model and its interior were painted in black. The lower half of the model was painted in red. Figure 28b illustrates the upper cover of the model. A rubber tube of 4 *mm*-diameter and 0.5 *m*-length was used as a vent for the water tank to enable air movement to/from the tank. Rubber strips and silicone sealant were used for complete water-proofing of *RCSS* model. Front and rear views of *RCSS* model are shown in Fig. 28c. A complete view of *RCSS* model is shown in Fig. 28d.

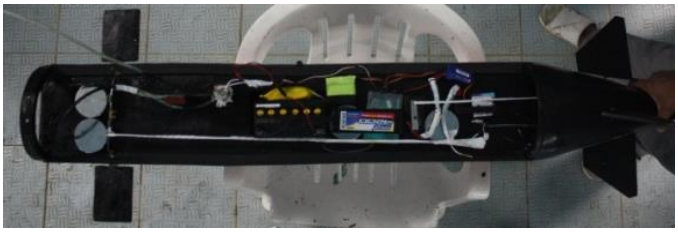
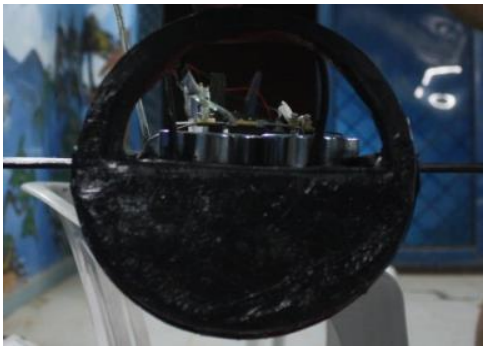
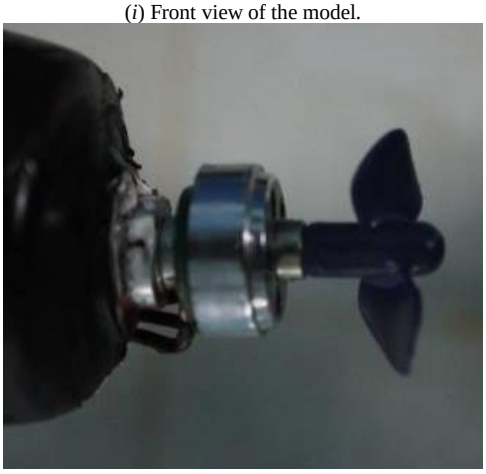


Fig. 28a. Assembeled components inside *RCSS* moel.

Fig. 28b. Upper cover of *RCSS* model.



(*i*) Front view of the model.



(*ii*) Rear view of the model (propeller).

Fig. 28c. Front and rear views of *RCSS* model.

Fig. 28d. Complete view of *RCSS* model.

VI. Operation and Testing of RCSS Model

The model was operated and tested in a swimming pool. The operation was restricted to surface cruising. Tests covered the following items, which were performed successfully:

(i) Radio control unit: inspecting the response of the model to different signals, Fig. 29a.
(ii) Cruising and orientation: by controlling the two vertical rudders, Fig. 29b.
(iii) Forward and reverse motion: by reversing the rotation direction of the propeller, Fig. 29c.
(iv) Movement of the four front and rear horizontal rudders: although there was no diving.

Fig. 29a. Inspection of radio control unit.

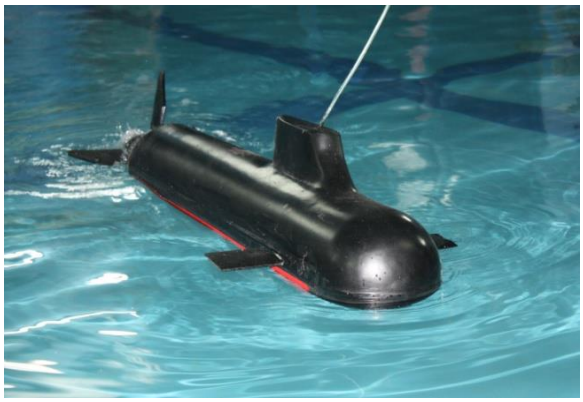


Fig. 29b. Cruising and orientation by vertical rudders.

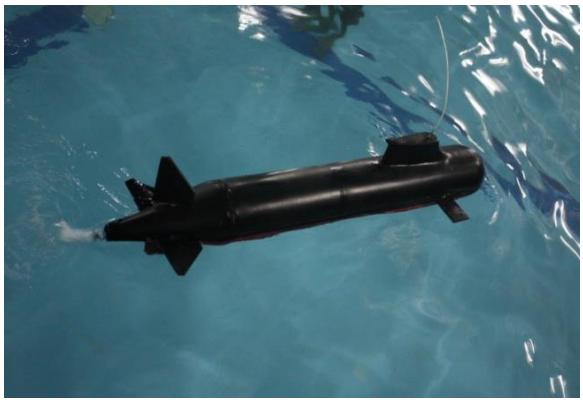


Fig. 29c (i) Forward.

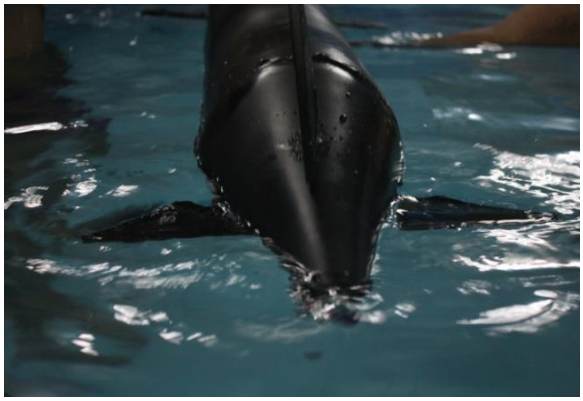


Fig. 29c (ii) Reverse.

Fig. 29c. Forward and reverse motion by controlling rotational direction of the propeller.

Fig. 29. Operation and Testing of *RCSS* Model.

However, diving test of the model failed due to improper operation of the water pump. The pump failed to fill the water tank of *RCSS* model. Thus, this test was postponed for a following phase.

VII. Conclusions

The stages of design, construction, and operation of *RCSS* model were illustrated in the present paper. This work was intended to be carried out by engineering students for self-learning and hands-on experience in multidisciplinary engineering topics.

Based on the above clarifications and operational tests, the following points can be stated:

1- The tests of the radio control unit were successful within the maximum operating range of the unit (180 *m*).
2- Material selection of the model hull (fiberglass) proved to be a good choice.
3- In spite of its small size and low power consumption, the waterproof motor-propeller unit was capable of driving the relatively big-size model.
4- The wet battery was capable of powering the driving motor-propeller unit and servo-motors for about an hour. This period was sufficient to carry out all needed operation and test.

As the operation of the water pump failed, the diving operation of *RCSS* model was not carried out. It is recommended for further development in a future phase to concern the diving operation and test of the model.

Acknowledgment

This work was carried out by the students as being members of the team of a B.Sc. Graduation Project under the supervision of *Prof. Dr.* Ahmed Farouk AbdelGawad, College of Engineering and Islamic Architecture, Umm Al-Qura University, Mekkah, Saudi Arabia.

NOMENCLATURE

DC : Direct current
ESC : Electronic speed control
PWM : Pulse width modulation
RCSS : Radio-controlled submersible ship (submarine)
RPM : Revolution Per Minute
SSBN : Ballistic missile submarines
SSN : Nuclear-powered submersible ship (submarine)

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